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Accuracy of commercial 3D printers for the fabrication of surgical guides in dental implantology

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Objectives: To evaluate the accuracy of two different surgical guides (small extent = single implant and large extent = full arch) fabricated by five additive manufacturing technologies (SLA=Stereolithography, DLP= Digital Light Processing, FDM=Fused Deposition Modeling, SLS=Selective Laser Sintering, Inkjet).

Methods: Overall, 72 guides (6 per type) were obtained with the different machines (SLA=Form2; DLP=Rapid Shape D40 and Cara Print 4.0; FDM=Raise 3D Pro2; SLS=Prodways P1000; Polyjet[®]=Stratasys J750). The guides were surface-scanned with an optical dental scanner, and the resulting files were compared with the initial design files using a surface matching software. Root Mean Square (RMS) and standard deviation were calculated, representing respectively trueness and precision. Kruskal-Wallis non-parametric test was used to compare trueness and precision between small-extent and large-extent guides and 3D printer by pairs. The threshold for significance was $\alpha=0.05$, except for the comparison of printers by pairs where a Bonferroni-corrected level of 0.0033 was used.

Results: Significant differences were observed for trueness and precision between small-extent and large-extent guides, regardless the printer except for DLP (trueness and precision) and SLS (precision). SLA, DLP and Polyjet[®] technologies showed similar results in terms of trueness and precision for both small-extend and large-extend guides ($P>0.05$).

Conclusions: The size affected the accuracy of CAD-CAM surgical guides. The different additive manufacturing technologies had a limited impact on the accuracy.

Clinical Significance: This study is of major clinical interest as it shows that accuracy of surgical guides manufactured with SLA/DLP technologies finding final clinical applications due to the biocompatibility of the resin, is similar. However, the size of the guide (small-extent versus large-extent) improve a statistically significant difference on the accuracy of 3D printing.

1. INTRODUCTION

The accurate placement of dental implants is crucial to prevent lesions of anatomical structures and to optimize prosthetic rehabilitation, leading to a long-term clinical success. Consequently, various computer-aided implant surgery have been developed in order to optimize the placement of dental implants [1]. Hämmerle et al. [2], differentiates computer-guided surgery from computer-navigated surgery. On one hand, computer-navigated surgery is a dynamic assistance that requires a surgical navigation system to reproduce virtually the drilling planning directly from computerized tomographic data. This system allows “live” intraoperative changes in implant position. On the other hand, computer-guided surgery is a static assistance that requires a physical surgical guide. The guide is 3D-printed and reproduces the virtual drilling planning directly from computerized tomographic and surfacic data. Guided surgery, compared to traditional techniques, allows to a more accurate implant placement. Indeed, computer-guided surgery was shown to provide more accuracy than freehand surgery [3,4] when compared to either semi-guided, fully-guided [5], or computer-navigated surgery [6]. Among the surgical guides, the “full-guided” guide offers more guarantees to control the drill angulation, depth and location of the implant. This technique is associated with reduced surgical time, reduced invasiveness and optimal prosthetic results. Currently, fully-guided or “fully constrained” surgery is considered as the most reproducible technique for placing an implant [7]. However, bias in implant placement are still reported.

Several studies have compared the position of the placed implant with respect to planning for both (x,y,z) axis and angulation. The deviation between the planned and effective implant position can be caused by multiple factors. Based on the literature, the error factors can be classified in three categories (i) clinical situation derived factor [8,9], (ii) implant system derived factors [10] and (iii) surgical guide design [11,12] and manufacturing derived factor [13,14]. For example, Putra et al. [15] showed in a literature review that guides produced by a conventional method induce a higher angular deviation than a 3D-printed guide.

The manufacturing of a surgical guide for guided implant surgery requires three steps: (i) acquisition of patient data, (ii) data processing, (iii) guide manufacturing. The data acquisition consists in capturing the patient's bone geometry via a Cone Beam Computed Tomography (CBCT) or CT-scan exam in the Digital Imaging and Communication in Medicine (DICOM) format. In parallel, the surface geometry is registered via optical scanning (3D intra-oral scanner, IOS) and processed to obtain a digital model in Standard Tessellation Language (STL) format. Then, a dedicated software allows the matching of DICOM and STL file, to plan the surgery, and to design a surgical guide. The ready-to-print STL file of the guide is then exported.

The most common 3D-printing technologies used to fabricate surgical guides in dental implantology are stereolithography (SLA), Digital Light Processing (DLP), inkjet and its derivative PolyJet[®]. However, there are other AM technologies available such as Selective Laser Sintering (SLS), 3-Dimensional Printing (3DP) and Fused Deposition Modeling (FDM). Although a variety of materials can be used with these technologies, plastics, resin or plastic-based materials are the most commonly used materials for dental applications [16]. Chen et al. [17] have also used Direct Metal Printing (DMP) technology to manufacture Co-Cr surgical guides but this technology is not widely used for this application probably because its use is more complex and the overall costs (including printer device and consumables) are higher than resin printers. However, SLA was until recently the most used technology for guide manufacturing, and resin guides were often called “stereolithographic guides” in the surgical literature.

SLA is a process based on the polymerization of monomer resin by a laser beam. After creating a layer, the moving platform is lowered into the reservoir tank and this process

continues layer-by-layer until the printed part is completed [18]. DLP is also a vat-photopolymerization technology according to the American Society for Testing Material (ASTM). The main difference between SLA and DLP is the light source. The DLP system takes advantage of a digital micromirror device (DMD) to project a mask of light that allows a layer to be cured in a few seconds [19]. In one hand, according to Taormina et al. [20], a faster 3D construction process would lead to intrinsic lesser accuracy. In the other Hand, SLA provides a smaller minimum feature size thanks to a laser spot size smaller than the minimum pixel size of the DMD.

PolyJet[®] printing is also based on a layer-by-layer technology. The process consists in the selective deposition of material droplets onto the building platform and their immediate solidification by a light source (usually a UV lamp attached to the print heads), allowing layers to be built up [21,22]. The main advantages of this technology are good print resolution and the possibility to print simultaneously a wide range of material, such as plastics, resins and elastomers, simultaneously, and color parts. Limitations include the high cost of the device and the instability of the resin-based materials overtime, that is a common problem to all resin-based technologies.

SLS technology uses a high-power laser beam that selectively irradiates a powder bed to produce localized thermal sintering. While the material partially absorbs at the laser source wavelength, irradiation induces locally elevated temperatures, allowing sintering to occur, i.e., powder particle sintering without melting [23].

In FDM manufacturing process, a filament of material is put through a heated nozzle head and melt for extrusion. Then the material is printed layer-by-layer on a receiving platform [24].

The popularity of AM surgical guides increases due to their accuracy, associated with reduced cost, reduced surgical time, and customization to patient's geometry for subsequent patient and surgeon benefits. The accuracy of surgical guides is therefore dependent on the 3D-printing technique and method involved for their fabrication.

The aim of this study was to evaluate trueness and precision of surgical guides fabricated by five different commercial AM technologies (SLA, DLP, FDM, SLS and Inkjet). Moreover, each AM technology was evaluated for trueness and precision using two different surgical guides (small extent = single implant and large extent = full arch). The null hypotheses were that AM technology and surgical guide size did not affect trueness and precision of CAD-CAM surgical guides.

2. MATERIAL AND METHODS

2.1. Surgical planning

The CoDiagnostix[®] (Straumann group, Basel, Switzerland), software was used for planning guided implant surgery in two patients. The first case (large-extent Surgical Guide (SG)) was a full-arch guide to place four implants in the mandible, with two lateral anchor pins. The second case (small-extent SG) aimed to place a single implant (tooth #11) and it was limited to two adjacent teeth (Figures 1a and 1b). STL files of both guides were obtained for the two planifications.

2.2. Surgical guides fabrication

Each surgical guide was 3D-printed using five different AM technologies SLA, DLP, FDM, SLS and PolyJet[®]. Each type of guide was printed six times with each technique to evaluate the internal accuracy.

Surgical guides printed by SLA were produced with a Form2 desktop printer (Formlabs Inc, Somerville, MA, USA) and a biocompatible photo-curable resin Dental SG[®] (Formlabs

Inc, Somerville, MA, USA) was used. The guides were printed with a platform inclination of 15°. A post-printing UV treatment was applied, according to the manufacturer's recommendations.

Surgical guides printed by DLP technologies were produced with two different commercial devices. The first device was a Rapid Shape D40 (Rapid Shape, Heimsheim, Germany) printer, and the biocompatible resin Sheraprint SG 100 (SHERA Werkstoff-Technologie GmbH & Co.KG, Lemförde, Germany) was used. The second device was a Cara Print 4.0 (Kulzer GmbH, Hanau, Germany) printer, and the biocompatible resin Dima Print Guide (Kulzer GmbH, Hanau, Germany) was used. The guides were printed without platform inclination. A post-printing UV treatment was applied, according to the manufacturers' recommendations.

Surgical guides printed by FDM were produced with a Raise 3D Pro2 printer (Raise 3D Technologies Inc, Irvine, CA, USA), and a Premium PLA filament (Raise 3D Technologies Inc, Irvine, CA, USA) was used. The guides were printed with a platform inclination of 60°.

Surgical guides printed by SLS were produced with a Prodways P1000 (Prodways Group, Paris, France), and a polyamide powder PA12-L 1600 (Prodways Group, Paris, France) was used. The guides were printed without platform inclination.

Surgical guides printed by Polyjet® were produced using Stratasys J750 printer (Stratasys Ltd, Eden Prairie, MN, USA) and a photosensitive polymer liquid VeroWhitePlus™ (Stratasys Ltd, Eden Prairie, MN, USA) was used.

Finally, 72 samples were obtained (2 guides design, 6 printers, 6 replicates). Figure 1c displays the large extent SG produced with different printing techniques.

2.3. Surface scanning, image analysis of the surgical guide and statistical analysis

After the fabrication, the guides were coated by the dental technician with an anti-reflective spray (Helling 3D Scan Spray; Laser design, MN, USA), and they were surface scanned with a tridimensional dental scanner (CARES 7 Series; Straumann group, Basel, Switzerland). The spray had an average thickness of 2.8 µm. The resulting STL files were compared with the initial design files using a surface matching software (Geomagic Control X®; 3D System Inc, Morrisville, NC, USA). In order to ensure relevant and pertinent calculations, only the underside surface guide sections facing the occlusal areas and surgical fixations pins were included in the analysis.

To describe the accuracy of a measurement method, the International Organization for Standardization (ISO) uses the combination of two terms, “trueness” and “precision” [25]. Trueness was given by the Root Mean Square (RMS), which was used to calculate the mean of the average absolute discrepancy between the initial design file and the STL file obtained after scanning the surgical guide. Precision was given by the Standard Deviation (SD), which allowed to calculate the dimensional discrepancies between the initial design file and the .STL file obtained after scanning the surgical guide [26]. A low RMS value revealed high trueness and a low SD value revealed high precision. Low RMS/SD values revealed high accuracy.

Due to the small sample size, we have used the Kruskal-Wallis non-parametric test to compare trueness and precision between small-extent SG and large-extent SG; the same test was used to compare trueness and precision obtained using the different commercial 3D printer two-by-two. The statistical threshold for statistical significance was $\alpha=0.05$, except for the comparison of printers two-by-two where a Bonferroni corrected significance level of 0.0033 was used. XLSTAT® software (Addinsoft, Paris, France) was used for these calculations.

3. RESULTS

The surface matching allowed to obtain a color map of the surfaces according to the measured difference between the initial STL file and the scanned file (Figure 2). Green color showed a surface matching of ± 0.1 mm. Areas in blue (negative divergence) indicated a smaller surgical guide, while areas in yellow, orange and red (positive divergence) indicated a larger surgical guide than the corresponding initial STL file.

3.1. Trueness

For the small-extent SG, Rapid Shape D40 obtained the lowest RMS value ($64.28 \pm 7.95 \mu\text{m}$) followed by Form2 ($67.75 \pm 10.63 \mu\text{m}$), Stratasys J750 ($70.43 \pm 5.41 \mu\text{m}$), Cara Print 4.0 ($75.53 \pm 13.95 \mu\text{m}$), Prodways P1000 ($97.93 \pm 13.62 \mu\text{m}$) and Raise 3D Pro2 ($104.33 \pm 22.24 \mu\text{m}$) (Table 1).

The RMS value remained similar for the printers Stratasys J750, Form2, Rapid Shape D40 and Cara Print 4.0 (Figure 3a). Besides, these printers performed no significant differences in two-by-two Kruskal-Wallis non parametric test with Bonferroni correction (table 2). Likewise, the RMS value was similar for the printers Prodways P1000 and Raise 3D Pro2 with no significant differences (Figure 3a). However, there was a significant difference in the trueness of small-extent SG between Raise 3D Pro2 and Form2 ($p=0.002$), between Raise 3D Pro2 and Rapid Shape D40 ($p=0.001$), between Prodways P1000 and Form2 ($p=0.002$), between Prodways P1000 and Rapid Shape D40 ($p=0.001$) (Table 2).

On the other hand, for the large-extent SG, Form2 obtained the lowest RMS Value ($93.12 \pm 13.22 \mu\text{m}$) followed by Cara Print 4.0 ($98.67 \pm 25.57 \mu\text{m}$), Rapid Shape D40 ($106.52 \pm 23.74 \mu\text{m}$), Stratasys J750 ($109.02 \pm 18.59 \mu\text{m}$), Prodways P1000 ($125.60 \pm 21.57 \mu\text{m}$) and Raise 3D Pro2 ($139.55 \pm 22.44 \mu\text{m}$).

The RMS value remained similar for the printers Form2, Cara Print 4.0, Rapid Shape D40, Stratasys J750 and Prodways P100 (Figure 4a). Besides, these printers performed no significant differences in the two-by-two Kruskal-Wallis non parametric test with Bonferroni correction. However, there was a significant difference in the trueness of large-extent SG only between Raise 3D Pro2 and Form2 ($p=0.001$) (Table 3).

The RMS values was not similar for printing small-extent or large-extent SG guide with the same commercial printer (Table 1). Significant statistical differences were observed between small-extent SG and large-extent SG, regardless of the commercial printer except for Cara Print 4.0 ($p=0.055$) (Figure 5a).

3.2. Precision

For the small-extent SG, Rapid Shape D40 obtained the lowest SD Value ($64.02 \pm 7.17 \mu\text{m}$) followed by Form2 ($64.30 \pm 9.83 \mu\text{m}$), Stratasys J750 ($70.02 \pm 5.43 \mu\text{m}$), Cara Print 4.0 ($72.65 \pm 16.61 \mu\text{m}$), Raise 3D Pro2 ($95.12 \pm 12.17 \mu\text{m}$) and Prodways P1000 ($97.82 \pm 13.04 \mu\text{m}$) (Table 1).

The SD value remained similar for the printers Stratasys J750, Form2, Rapid Shape D40 and Cara Print 4.0 (Figure 3b). Besides, these printers performed no significant differences in two-by-two Kruskal-Wallis non parametric test with Bonferroni correction (Table 4). Likewise, the SD value was similar for the printers Prodways P1000 and Raise 3D Pro2 with no significant differences (Figure 3b). However, there was a significant difference in the precision of small-extent SG between Raise 3D Pro2 and Form2 ($p=0.002$), between Raise 3D Pro2 and Rapid Shape D40 ($p=0.002$), between Prodways P1000 and Form2 ($p=0.001$), between Prodways P1000 and Rapid Shape D40 ($p=0.001$) (Table 4).

On the other hand, Cara Print 4.0 obtained the lowest SD value ($94.10 \pm 19.05 \mu\text{m}$) followed by Form2 ($98.05 \pm 12.16 \mu\text{m}$), Rapid Shape D40 ($101.22 \pm 21.04 \mu\text{m}$), Stratasys J750

($110.47 \pm 19.36\mu\text{m}$), Prodways P1000 ($111.47 \pm 25.88\mu\text{m}$) and Raise 3D Pro2 ($139.62 \pm 20.05\mu\text{m}$) for the large-extent SG (Table 1).

The SD values remained similar for the printers Form2, Cara Print 4.0, Rapid Shape D40, Stratasys J750 and Prodways P100 (Figure 4b). Besides, these printers performed no significant differences in the two-by-two Kruskal-Wallis non parametric test with Bonferroni correction. However, there was a significant difference in the precision of large-extent SG only between Raise 3D Pro2 and Cara Print 4.0 ($p=0.002$) (Table 5).

The SD values were not similar for printing small-extent or large-extent SG guide with the same commercial printer (Table 1). Significant statistical differences were observed between small-extent SG and large-extent SG regardless of the commercial printer except for Cara Print 4.0 ($p=0.078$) and Prodways P1000 ($p= 0.423$) (Figure 5b).

4. DISCUSSION

Null hypotheses were rejected in the basis of statistical analysis of the results, as additive manufacturing technology and surgical guide size affected accuracy and reproducibility of CAD-CAM surgical guides. Many factors can affect accuracy and reproducibility of 3D printed surgical guides, including data acquisition, data processing and surgical guides manufacturing. These depend on the 3D printer as well as on the dental technician using the device. An accuracy defect leads to a deviation of the implant positioning. It is therefore necessary to identify factors and study them individually, in order to improve accuracy and reproducibility. The present study evaluated the influence of AM technology on trueness and precision, as well as the influence of the guide size.

First, the trueness and the precision of each printer were compared, according to the guides size. Small-extent SG exhibited overall higher trueness and precision than large-extent SG. Statistical Kruskal-Wallis test showed a significant difference for most printers when comparing small-extent to large-extent guides. Exceptions were DLP (Cara Print 4.0) for trueness and precision and SLS (Prodways P1000) for precision. These results were in accordance with Kholy et al. [27], who had studied influence of surgical guide support on accuracy of implant site location. The authors showed that an implant placed by a surgical guide supported by four teeth exhibited 3D deviation values similar to implants placed with full-arch guides. However, surgical guides supported by only two teeth demonstrated significantly higher deviation values than implants placed using surgical guides supported by four teeth or more. Moreover, Matsumura et al. [10] showed that an insufficient number of teeth supporting the guide, or an excess of teeth supporting the guide can influence errors of implant positioning during guided surgery. Balance fit and stability were therefore not sufficient to allow an accurate implant placement. Further studies are needed to determine the threshold guide size for which both guide accuracy and correct implant placement position can be optimized.

Trueness and precision were also compared between the different printers, for both small-extent SG and large-extent SG. For small-extent SG DLP (Rapid Shape D40) and SLA (Form2) printing technologies showed the lower RMS and SD value, while FDM (Raise 3D Pro2) and SLS (Prodways P1000) printing technologies showed the higher RMS and SD value. According to the Kruskal-wallis statistical test, there is a significant difference between the two groups. For the large-extent SG, the statistical differences are less pronounced. These results were different from observations by Kim et al [22], who reported a significant difference in trueness and precision between Polyjet® and DLP on the one hand and SLA and FDM on the other hand. It should be noted, however, that the printers in our study were produced by different manufacturers. Interestingly, Li et al. [17] compared two technologies, Polyjet® and SLA, from the same manufacturers and reported a significant difference between the two technologies. On the opposite, our study found no significant difference between the Polyjet®

and SLA technologies. Our Polyjet printer (Stratasys J750) was different that the model used by Li et al. [17] (Eden260VS Stratasys Ltd, Eden Prairie, MN, USA).

In another field of health application, a study by Salmi et al. [28] compared 3D skull models printed with SLS, 3DP and Polyjet[®] techniques. They reported that the models printed with the Polyjet[®] printer had the smallest dimensional error, followed by models printed with 3DP and SLS. In another study, Ibrahim et al. [29] have printed mandibular models using SLS, 3DP and Polyjet[®]. The dimensional error was lowest for the SLS technique, followed by Polyjet and 3DP. Taehum et al. [30] have printed a simplified surgical guide with 3 technologies i.e. SLA, Polyjet[®] and Multijet Printing (MJP): they concluded that Polyjet[®] and SLA technologies had the best accuracy compared to the MJP technique. Although 3DP and MJP techniques were not used in our study, no significant difference was reported between the Polyjet[®] and SLS systems or Polyjet[®] and SLA. Moreover, the accuracy of 3D printers can differ depending on the nature of the printed materials. When manufacturing surgical guides involving photosensitive resin, errors could occur during the production and curing of the materials. The polymerization of the resin, the residual processing, the creation and removal of support structures (to avoid unsupported or weakly supported parts) can have an impact on the final result [31–33]. Thus, Piedra-Cascón et al [34] have studied impact of 3D-printing parameters, supporting structures, slicing, and post-processing procedures of vat-polymerization additive manufacturing technologies. Authors shown via a narrative study that the accuracy of the manufactured dental device is significantly influenced by these parameters. For example, they recommended to re-calibrate the printing parameters for each resin available for the printer.

The accuracy of the scanner used in our study to obtain the STL files may have influenced the results. Indeed, dental laboratory scanners showed an accuracy of about 10-15 μm . Compared to dental laboratory scanners, industrial scanners can offer a higher level of accuracy (5-7 μm) [35,36]. In the present study, Helling 3D Scan Spray was used with minimal material thickness on all guides during the scanning procedure with the laboratory laser scanner, which was set to an accuracy of 15 μm to improve the consistency of the scan results [37]. However, as all the samples were processed with the same procedure, it can be assumed that the dental laboratory scanner and the powdering of the SG did not influence the comparisons between the printers.

To study the printing accuracy of the different 3D printers, the RMS value given by the Geomagic software was used. These determinants have also been used in different studies and have shown their value [26,38,39]. Other methods could have been used as described elsewhere [40] such as the absolute average (ABS AVG) or the $(90^{\circ} - 10^{\circ})/2$ (where 90° is the 90th percentile and 10° is the 10th percentile).

In our study, only surgical guides manufactured with SLA/DLP technologies could find final clinical applications due to the biocompatibility of the resin. Indeed, surgical guides are manufactured using resin designed as class 1 materials and having the CE marking, which can be sterilized and used intraorally [41]. Many studies [42–44] have investigated the impact of sterilization procedure as a dimensional change in the manufactured guide. These studies agree that sterilization of any type (heat or plasma) does not have a significant impact on the dimensional changes of the guides tested. SLA and DLP technologies are similar and classified in the same category of AM by the ASTM. No significant difference between the SLA and DLP printers was observed for both small-extent SG and large-extent SG. These results are different from those obtained by Mangano et al. [45], who have studied the accuracy of six printers. In this study, 9 parallelepipeds were printed with 6 different 3D-printer, using the proprietary material and with the layer thickness indicated by the manufacturer for the fabrication of dentate models. The results have shown a significant difference between the models printed by SLA and DLP. This difference could be explained by the layer thickness (as suggested by the manufacturer). Similar observations were made by Rungrojwittayakul et al. [46] where the

different layer thickness might affect the dimensional accuracy of the model. Favero et al. [47] reached the same conclusion. The x-y-z resolution of each layer influence the surface accuracy of the device. Even the design of the base can influence 3D-printer accuracy as observed by Camarella et al. [48]. Indeed, they have shown that for the same SLA printer, the shape of the base (regular base vs horseshoe-shaped base) influenced the printing accuracy. In our study, the models were printed with different resolutions: equal layer thickness, x-y resolution, and manufacturing environments. All these parameters limit the generalization of these findings.

The intrinsic lesser accuracy of DLP compared to SLA did not impact the accuracy of the printed guides related to their size. However, two differences should be noted: the manufacturing of surgical guide is eight time longer for SLA (SLA≈4h; DLP≈30min) and the cost of the machines which ranges from 2-3 k€ for the SLA printer, compared to 5 to 100 k€ for the DLP printer.

Finally, further limitations of our study include the *in vitro* settings and the two surgical guides used. Further *in vitro* and clinical studies are needed to evaluate and compare the scanning accuracy of different printers in a larger variety of clinical situations.

5. CONCLUSION

Within the limitations of the present *in vitro* study, the small-extent surgical guides were more accurate than the large-extent guides, regardless of the 3D-printer technology. Nonetheless, SLA and DLP technologies showed similar results in terms of trueness and precision for both small-extent and large-extent surgical guides. FDM technology was the least accurate. Several parameters have an influence on the accuracy of the parts produced and we have shown that the type of 3D-printer matters in some cases. It's also important to consider other parameters such as the printing material, the use of supporting structures, the slicing method and the type of software, the use of a post-processing polymerization and other printing parameters. The adequate combination of these parameters is essential to obtain the best accuracy and reproducibility of the printed parts that are essential to obtain reliable surgical procedures. The minimum is to follow the process described by the manufacturer, but the dental technician has also an important role to optimize these parameters. Further studies are needed on each parameter involved, in order to identify critical processes that determine the best printing accuracy.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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7. TABLES

Table 1. Trueness and precision of commercial printers for the manufacturing of either small-extent surgical guide or large-extent surgical guide.

Commercial 3D Printers	Trueness/precision Mean (μm)	Small-extent surgical guide (mean \pm sd)	Large-extent surgical guide (mean \pm sd)	p-value* ($\alpha=0.05$)
Stratasys J750	Trueness	70.43 \pm 5.41	109.02 \pm 18.59	0.004
	Precision	70.02 \pm 5.43	110.47 \pm 19.36	0.004
Prodways P1000	Trueness	97.93 \pm 13.62	125.6 \pm 21.57	0.025
	Precision	97.82 \pm 13.04	111.47 \pm 25.88	0.423
Raise 3D Pro2	Trueness	104.33 \pm 22.24	139.55 \pm 22.44	0.037
	Precision	95.12 \pm 12.17	139.62 \pm 20.05	0.004
Form2	Trueness	67.75 \pm 10.63	93.12 \pm 13.22	0.010
	Precision	64.3 \pm 9.83	98.05 \pm 12.16	0.004
Rapid Shape D40	Trueness	64.28 \pm 7.95	106.52 \pm 23.74	0.006
	Precision	64.02 \pm 7.17	101.22 \pm 21.04	0.006
Cara Print 4.0	Trueness	75.53 \pm 13.95	98.67 \pm 25.57	0.055
	Precision	72.65 \pm 16.61	94.1 \pm 19.05	0.078

Sd=standard deviation; *calculated with Kruskal-Wallis test

Data obtained from a small-extent surgical guide and a large-extent surgical guide printed six times by each printer.

Table 2. P-values from two-by-two comparisons of trueness between the commercial 3D printers to manufacture a small-extent surgical guide (with Bonferroni corrected significance $\alpha=0.0033$)

	Stratasys J750	Prodways P1000	Raise 3D Pro2	Form2	Rapid Shape D40	Cara Print 4.0
Stratasys J750	1	0.018	0.015	0.502	0.304	0.722
Prodways P1000	0.018	1	0.934	0.002	0.001	0.045
Raise 3D Pro2	0.015	0.934	1	0.002	0.001	0.037
Form2	0.502	0.002	0.002	1	0.722	0.304
Rapid Shape D40	0.304	0.001	0.001	0.722	1	0.166
Cara Print 4.0	0.722	0.045	0.037	0.304	0.166	1

Table 3. P-values from two-by-two comparisons of trueness between the commercial 3D printers to manufacture a large-extent surgical guide (with Bonferroni corrected significance $\alpha=0.0033$)

	Stratasys J750	Prodways P1000	Raise 3D Pro2	Form2	Rapid Shape D40	Cara Print 4.0
Stratasys J750	1	0.255	0.053	0.212	0.934	0.502
Prodways P1000	0.255	1	0.427	0.017	0.223	0.071
Raise 3D Pro2	0.053	0.427	1	0.001	0.044	0.009
Form2	0.212	0.017	0.001	1	0.244	0.565
Rapid Shape D40	0.934	0.223	0.044	0.244	1	0.556
Cara Print 4.0	0.502	0.071	0.009	0.565	0.556	1

Table 4. P-values from two-by-two comparisons of precision between the commercial 3D printers to manufacture a small-extent surgical guide (with Bonferroni corrected significance $\alpha=0.0033$)

	Stratasys J750	Prodways P1000	Raise 3D Pro2	Form2	Rapid Shape D40	Cara Print 4.0
Stratasys J750	1	0.016	0.026	0.381	0.411	0.891
Prodways P1000	0.016	1	0.848	0.001	0.001	0.011
Raise 3D Pro2	0.026	0.848	1	0.002	0.002	0.018
Form2	0.381	0.001	0.002	1	0.956	0.459
Rapid Shape D40	0.411	0.001	0.002	0.956	1	0.493
Cara Print 4.0	0.891	0.011	0.018	0.459	0.493	1

Table 5. P-values from two-by-two comparisons of precision between the commercial 3D printers to manufacture a large-extent surgical guide (with Bonferroni corrected significance $\alpha=0.0033$)

	Stratasys J750	Prodways P1000	Raise 3D Pro2	Form2	Rapid Shape D40	Cara Print 4.0
Stratasys J750	1	1.000	0.080	0.298	0.493	0.179
Prodways P1000	1	1	0.080	0.298	0.493	0.179
Raise 3D Pro2	0.080	0.080	1	0.005	0.015	0.002
Form2	0.298	0.298	0.005	1	0.722	0.763
Rapid Shape D40	0.493	0.493	0.015	0.722	1	0.511
Cara Print 4.0	0.179	0.179	0.002	0.763	0.511	1

8. FIGURES

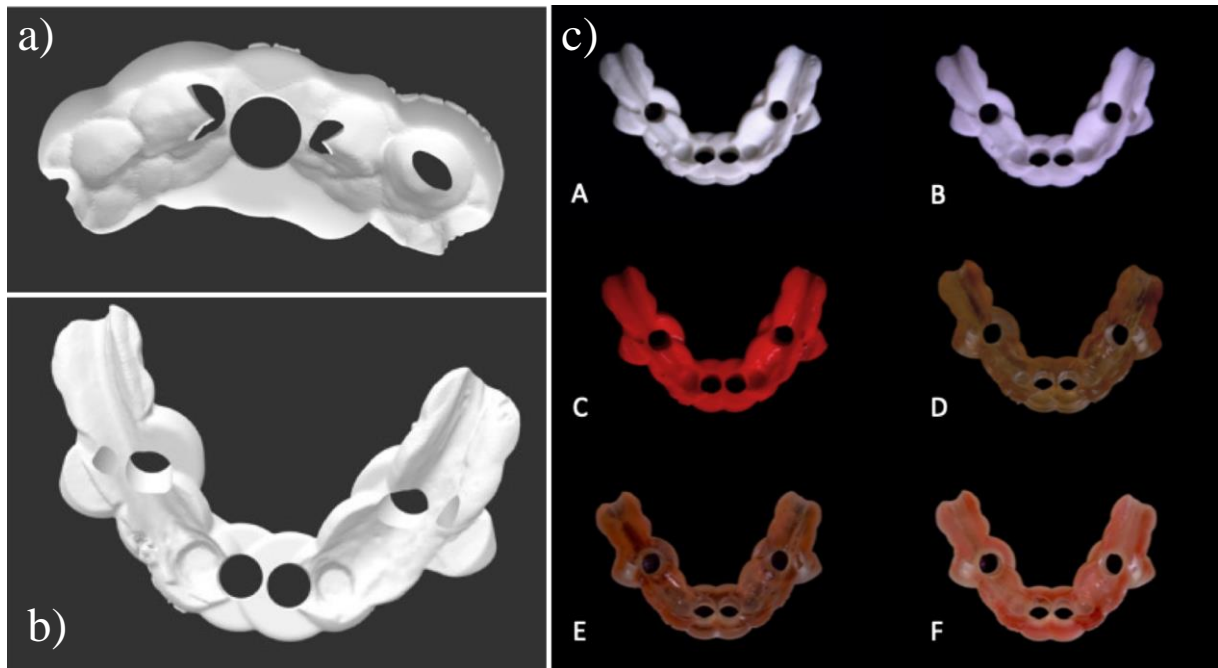


Figure 1. a) STL files of small-extent surgical guides and b) large-extent surgical guides. c) Large-extent surgical guides manufactured by A. Stratasys J750; B. Prodways P1000; C. Raise 3D Pro2; D. Form2; E. Rapid Shape D40; F. Cara Print 4.0.

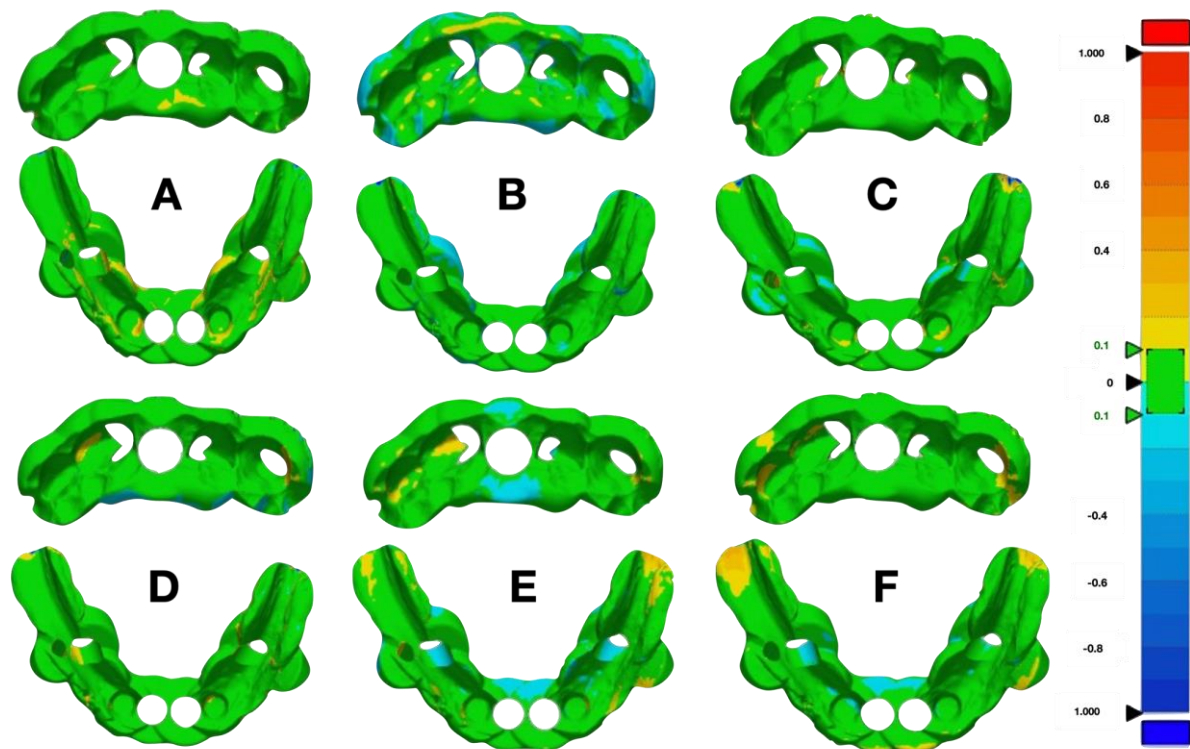


Figure 2. Colorimetric maps after superimposing the scanned guide with initial STL file. A. Stratasys J750; B. Prodways P1000; C. Raise 3D Pro2; D. Form2; E. Rapid Shape D40; F. Cara Print 4.0.

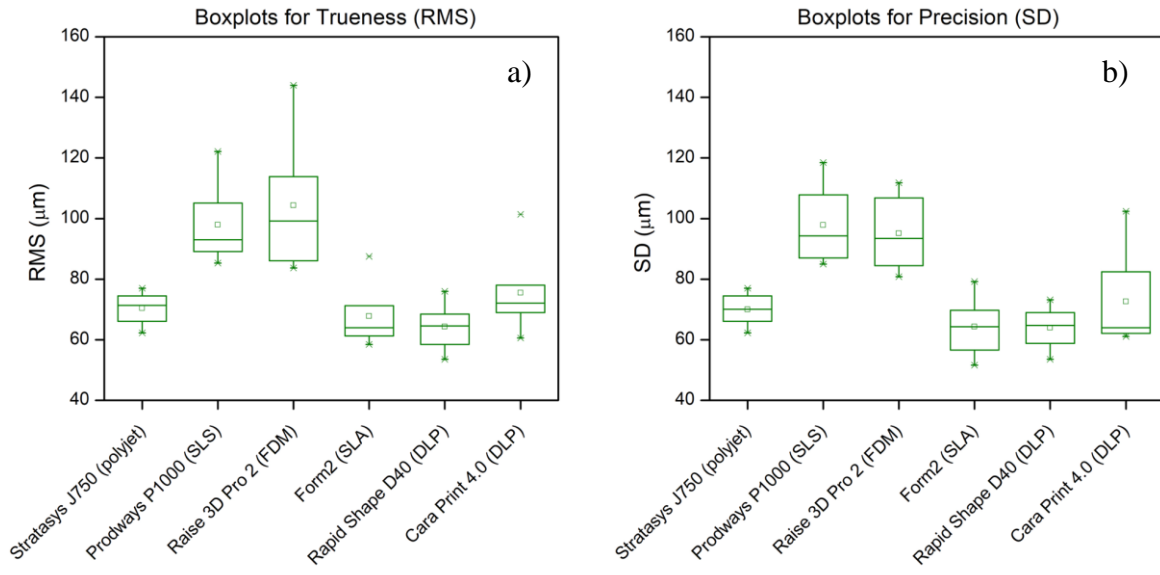


Figure 3. Boxplot of a) the trueness (RMS value) and b) the precision (SD value) obtained among the different 3D-printer devices for small-extent SG.

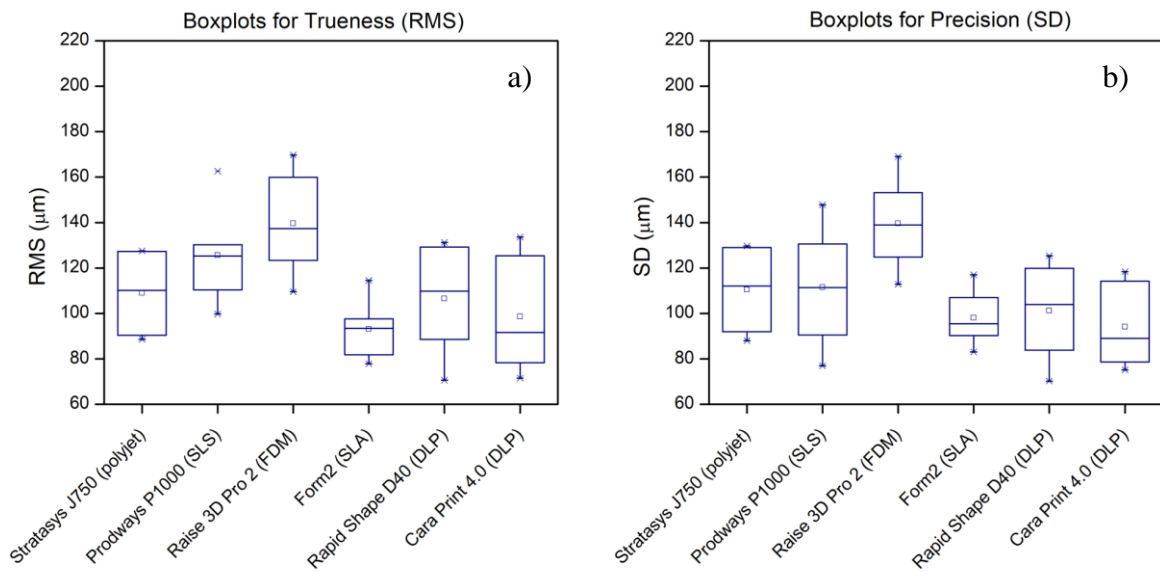


Figure 4. Boxplot of a) the trueness (RMS value) and b) the precision (SD value) obtained among the different 3D-printer devices for large-extent SG.

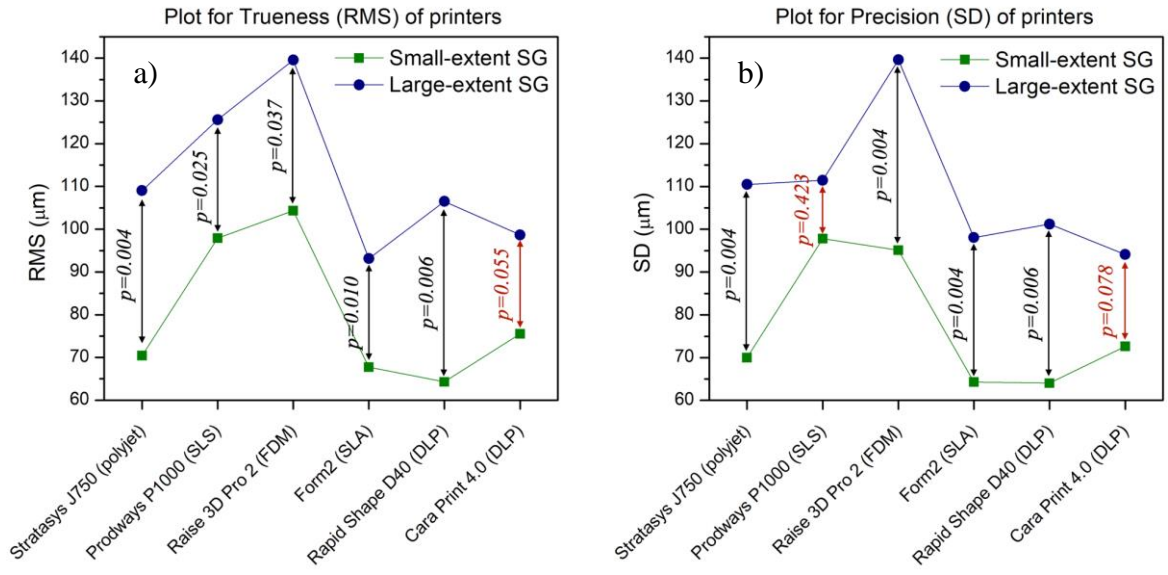


Figure 5. Impact of guide size (small-extent versus large-extent) for each printer to a) Trueness (RMS value) and b) Precision (SD value).